Robot Assisted MicroSurgery Development at JPL

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Abstract

A team of engineers at JPL, working in collaboration with MicroDexterity Systems, Inc and Dr. Steve Charles, recently developed a telerobotic workstation to assist microsurgeons perform surgery. The lightweight, compact 6 dof master-slave system developed is precise to better than 15 microns and can cover a workspace greater than 400 cubic centimeters. Current capabilities of the system include manual position control with augmented shared control modes and automatic modes of control of the robot. Force feedback from sensed forces of interaction at the slave is also reflected to the master device to enhance the sense of touch. Evaluation of the performance improvements enabled by the telerobot in simulated microsurgical tasks was recently performed. Prototypes of the telerobot have been used to demonstrate a single-arm simulated eye microsurgical procedure and a dual-arm microsurgical suturing procedure. Virtual Reality applications of this system include use of the input device as a haptic interface and in the use of virtual augmentation to the real-world feedback to improve operator performance.

Introduction

Microsurgeons use a microscope with 20 to 30 times magnification to help them visualize the microscopic field they work with. However, they still use their hands to hold instruments that manipulate tissue with feature sizes from fifty to a few hundred microns. A microsurgical manipulator that can scale down the surgeon's hand motions to the microscopic field would allow the average surgeon to perform at the level of the best surgeons and allow the most skillful surgeons to perform at unprecedented levels of dexterity[2]. Development of practical systems for assisting microsurgeons in this way is a growing field of research. Micro-telerobotic workstations systems that have been developed for bio-medical applications include those reported by Hunter[6], Dario[3,4] and Hannaford[5].

The work reported here is the result of collaboration between researchers at the Jet Propulsion Laboratory and Steve Charles, MD, a vitreo-retinal surgeon. The Robot Assisted MicroSurgery (RAMS) telerobotic workstation developed at JPL[1,14,15] is a prototype of a system that will be completely under the manual control of a surgeon. It is unique in its combination of compact size, light-weight and high precision. The system, shown on Figure 1, has a slave robot that will hold surgical instruments. The slave robot motions replicate in six degrees of freedom those of the surgeon's hand measured using a master input device with a surgical instrument shaped handle. The surgeon commands motions for the instrument by moving the handle on a master device in the desired trajectories. The trajectories are measured, filtered, and scaled down then used to drive the slave robot.

We present the details of this telerobotic system by first giving an overview of the subsystems and their interactions in the next section then present details in the following sections divided according to subsystem. This paper concludes with a description of a recent demonstration of a simulated microsurgery procedure performed at JPL.

Figure 1. RAMS telerobot system.

System description

Figure 2 shows an overview of the hardware components of the RAMS telerobotic system. Components of the RAMS system have been categorized into four subsystems (see Figure 3). They are the mechanical subsystem, the electronics subsystem, the servo-control subsystem and the high-level software subsystem. The mechanical subsystem consists of a master input device and a slave robot arm with associated motors, encoders, gears, cables, pulleys and linkages that cause the tip of the robot to move under computer control and to measure the surgeon's hand motions precisely.

The electronics subsystem consists of the motor amplifiers, a safety electronics circuit and relays within the amplifier box shown on Figure 2. These elements of the subsystem ensure that a number of error conditions are handled gracefully.

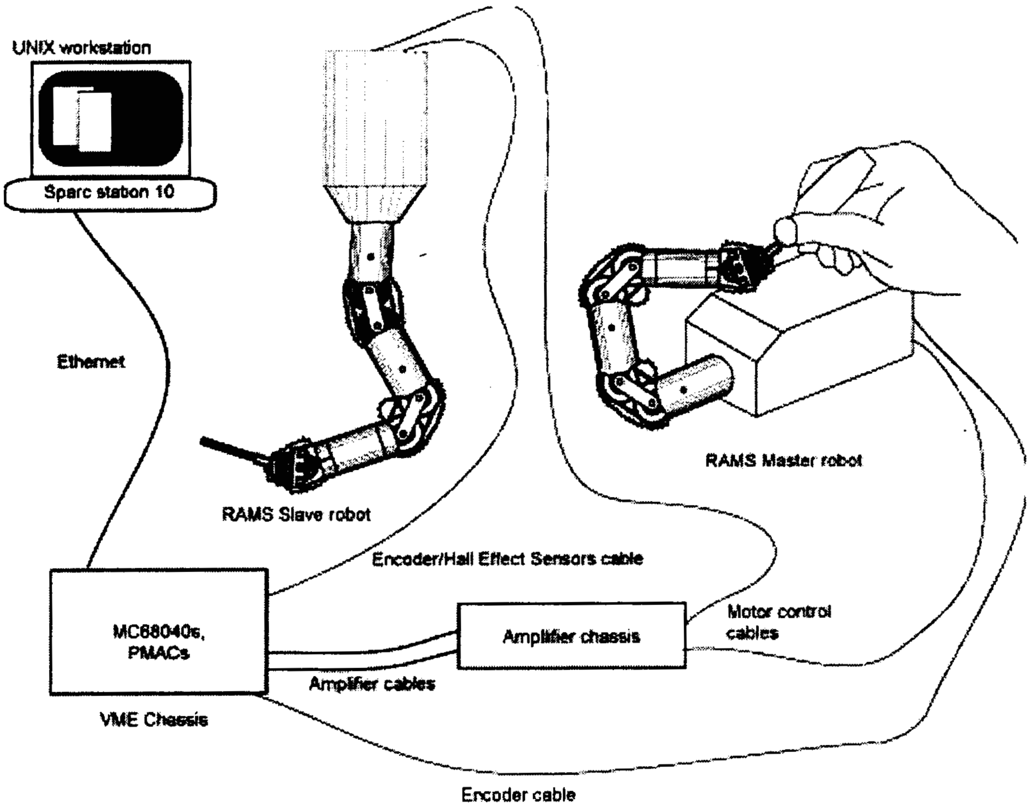

Figure 2. RAMS telerobot system.

The servo-control subsystem is implemented in hardware and software. The relevant hardware parts of the subsystem are the servo-control boards and the computational processor boards. Servo-control software functions include setting-up the control parameters and running the servo-loop on the servo-control board to control the six motors, implementing the communication between the computation and servo-control boards, initializing the servo-control system and communicating with the electronics subsystem and communicating with the high-level software subsystem. The high-level software subsystem interfaces with a user, controls initialization of the system software and hardware, implements a number of demonstration modes of robot control and computes both the forward and inverse kinematics. A drawing of the interaction between the subsystems of the RAMS slave robot is shown on Figure 3.

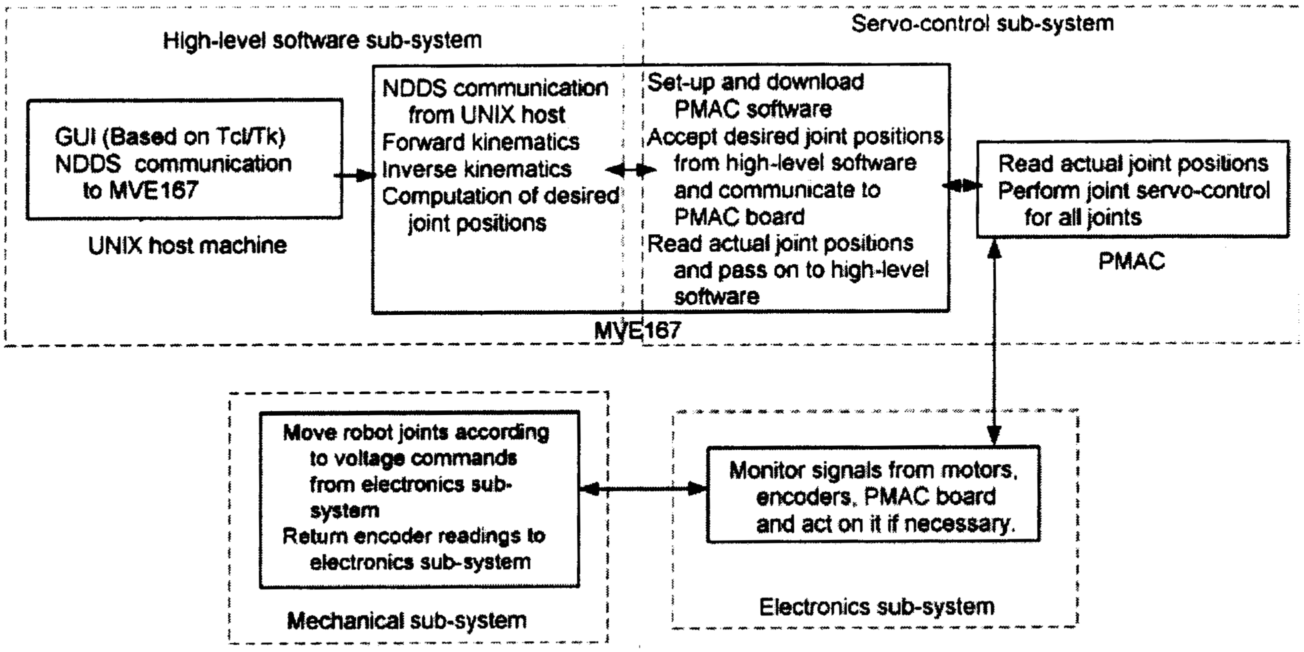

Figure 3. Sub-systems of the RAMS telerobot.

Mechanical subsystem

The RAMS slave manipulator is a six degrees-of-freedom tendon-driven robotic arm designed to be compact yet exhibit very precise 10 micron relative positioning capability as well as maintain a very high work volume. Physically, the arm measures 2.5 cm. in diameter and is 25.0 cm. long from its base to tip. It is mounted to a cylindrical base housing which measures 12 cm. in diameter by 18 cm long that contains all of the drives that actuate the arm. A photograph of the arm appears on Figure 4. The joints of the arm are

- a torso joint rotating about an axis aligned with the base axis and positioned at the point the arm emerges from its base,

- a shoulder joint rotating about two axes that are in the same plane and perpendicular to the preceding links,

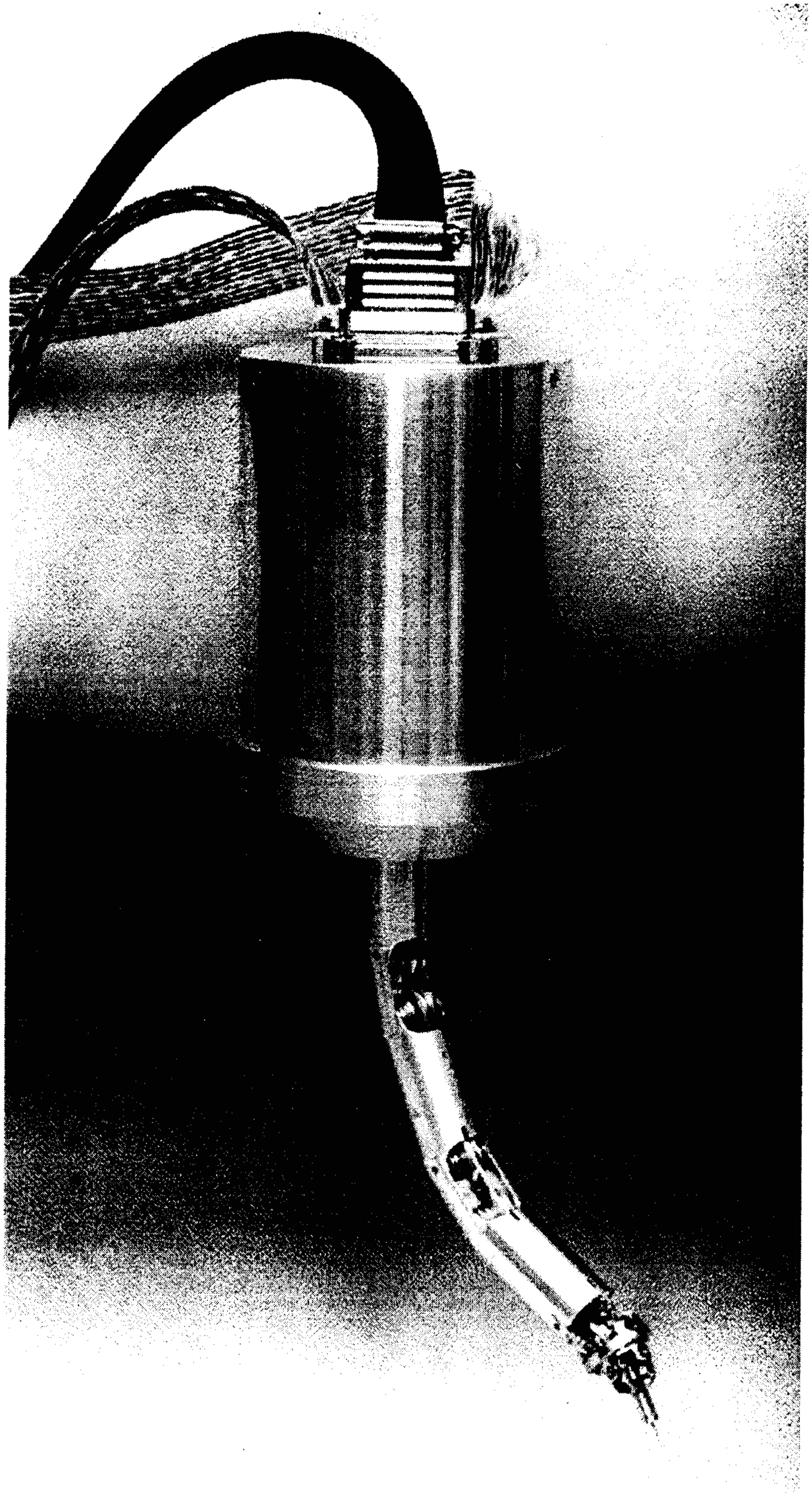

Figure 4. RAMS slave robot.

- an elbow joint that also rotates about two axes that are in the same plane and perpendicular to the preceding links, and
- a wrist joint consisting of pitch, yaw and roll rotations.

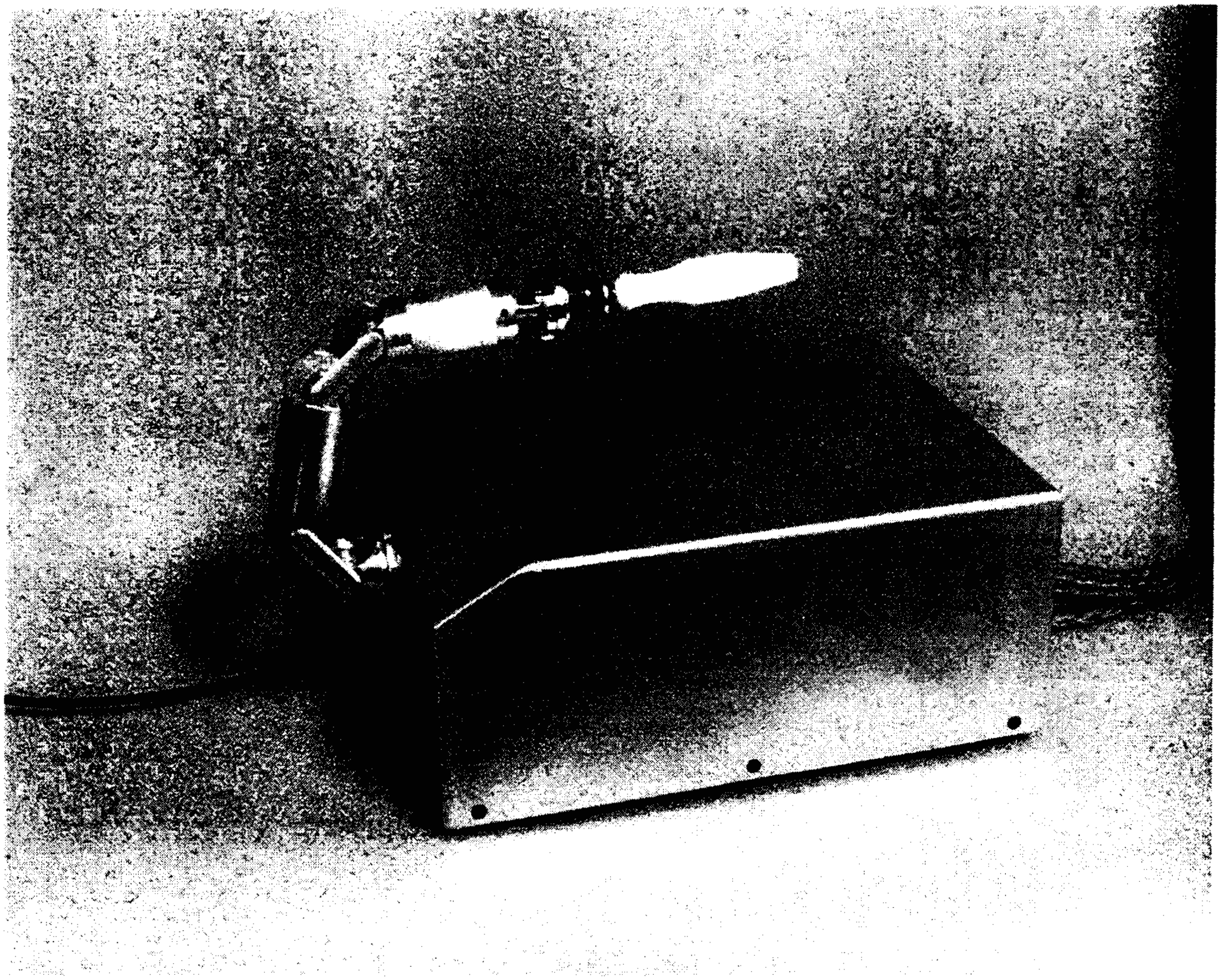

Figure 5. RAMS Master input device.

The master device, kinematically similar to the slave robot, also has six tendon-driven joints. It is 2.5 cm. in diameter and 25 cm. long. Its base houses high-resolution optical encoders requiring a larger volume - a box of size 10.8 cm by 18.4 cm by 23.5 cm. Gear transformation ratios in the master arm are reduced to allow backdrivability. A photograph of the master input device is shown on Figure 5.

The slave wrist design (based on the kinematics of the Rosheim OMNI-WRIST[13]) utilizes a dual universal joint to give a three degrees-of-freedom, singularity free, mechanically de-coupled joint that operates in a full hemisphere of motion (up to 90 degrees in any direction). The master wrist design uses a universal joint to transmit rotation motion through the joint while allowing pitch and yaw motions about the joint resulting in singularity free motion over a smaller range of motion in three degrees-of-freedom. The fourth and fifth axes of the master and slave robots are unique joints that rotate about 2 axes and allow passage of cables to pass through the joint for actuating the succeeding joints without affecting their cable lengths. The sixth axis is a torso joint, which simply rotates the manipulators relative to their base housing, For the slave robot the torso range of motion is 330 degrees while on the master it is 30 degrees.

Features resulting from the unique mechanical design of the arms are:

- Drive Unit Separability - Drive motors and optical encoders on the slave robot cannot survive an autoclave environment and are designed to be removable for sterilization.
- Zero/Low Backlash - Low backlash (free play) is essential for doing fine manipulation, especially since the position sensors are on the motor shafts.
- Low Stiction - Stiction (stick/slip characteristic) must be minimized to achieve small incremental movements without overshooting or instability.

- De-coupled Joints - Having all joints mechanically de-coupled simplifies kinematic computations as well as provides for partial functionality should any joint fail.
- Large Work Envelope - A large work volume is desirable so that the slave arm's base will not have to be repositioned frequently during tasks.
- High Stiffness - A stiff manipulator is necessary for accurate positioning under gravitational or environmental loads, especially when position sensing is at the motor drives.
- Backdrivability - The master arm has been designed to be easily backdrivable.
- Compact/Lightweight - In some applications, a restricted workspace warrants a small manipulator to minimize interference (i.e. visual interference).
- Fine Incremental Motions - Human dexterity limitations constrain surgical procedures to feature sizes of about 20-50 microns, whereas the slave arm is designed to achieve better than 10 microns relative positioning accuracy.
- Precise position measurement - The master arm has been designed to be able to measure commanded hand motions down to a relative position resolution of 25 microns, while the slave robot can read its tip position to a resolution of 1 micron.
- Tool Wiring Provisions - Tools requiring electrical or pneumatic power can have cabling routed through a passageway through both the master and slave arms.

The end effector of the slave robot is a force sensor instrumented micro-forceps actuated by a miniature DC motor. Simultaneous sensing of force interactions at the robot tip and manipulation with the forceps is possible with the end effector. Force interactions measured with the force sensor are processed and used to drive the master arm to amplify the sense of touch at the master handle. Figure 6 is a photo showing a close-up of the slave end effector.

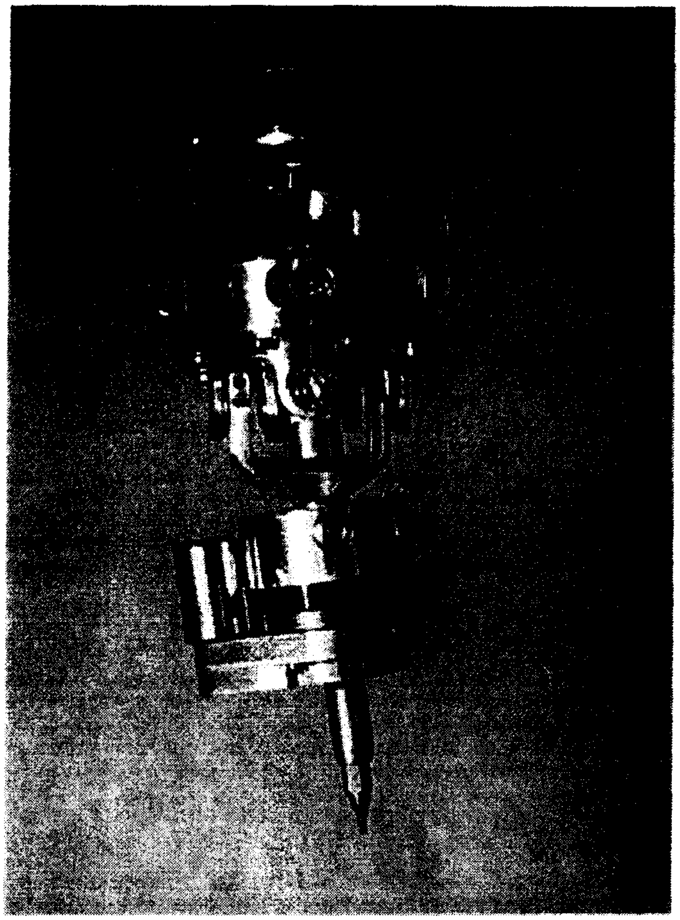

Figure 6. Slave robot end effector with force sensor and micro-forceps.

Electronics subsystem

The RAMS electronics subsystem design includes off the shelf and custom designed electronics. Figure 7 shows a layout of its general components. Components of the electronics subsystem are a VME chassis, an amplifier chassis and safety electronics. The VME chassis houses the VME backplane and three Motorola processor boards - one MVME-167 and two MVME-177 computer boards used for high-level system control. The VME chassis also contains two sets of PMAC servo control cards, power supplies (+/-15v) and two cable interface boards. The VME chassis front panel contains main power control (AC) for the system. The rear panel provides access to the control computer's serial communications port (RS-232). All components above are off-the-shelf items except the cable interface board.

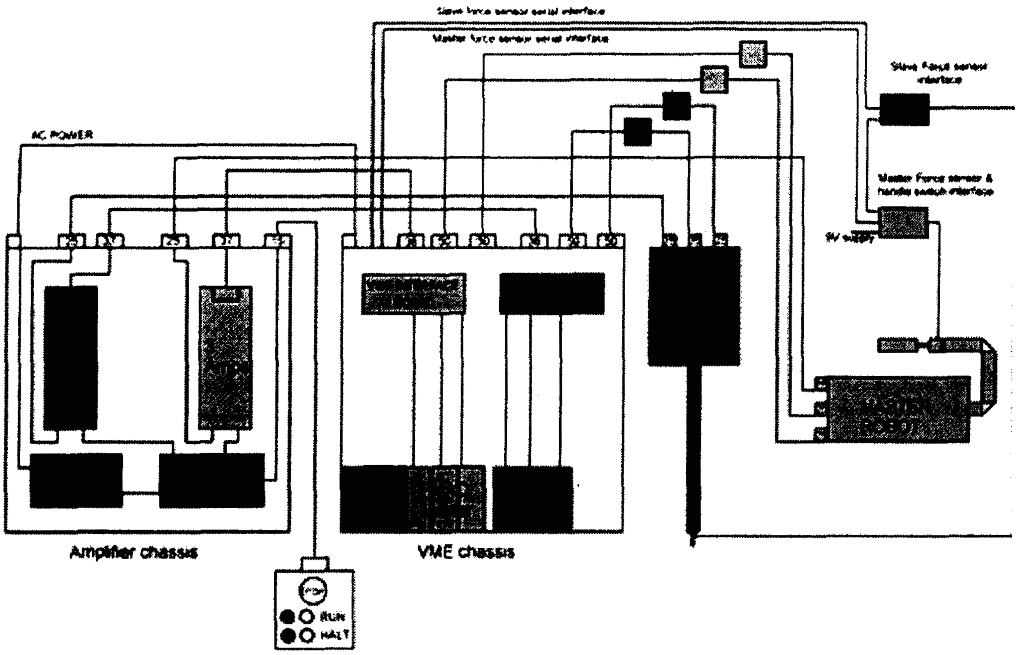

Figure 7. Electronics components and cabling.

The VME computer boards are the hardware portions of the high-level control system. The RS-232 interface provides communication for control and observation of the robot system functions. The PMAC servo boards generate 2 phase drive signals for sinusoidal commutation of the systems brushless DC motors. The PMAC receives optical encoder feedback from the motor shafts and provides low level control of the motors. The six I/O blocks and cable interface board handle signal and power distribution to the connectors on the rear panel.

The AMP (amplifier chassis) contains the six slave robot motor and three master robot motor drive amplifiers, system control electronics board, amplifier power supply and AMP subsystem power. The AMP chassis has interfaces to the VME chassis (analog inputs and control signals), the master and slave robot motor drive signals and to the CTRL panel subsystem (panic stop, run and initialize). The VME chassis provides the AMP chassis with its AC power.

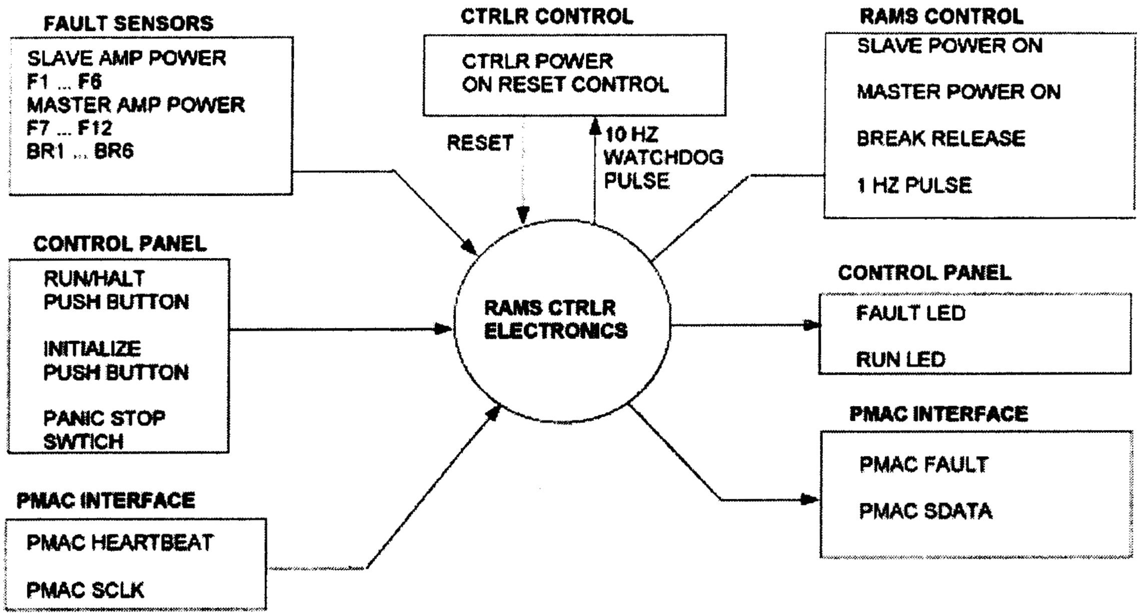

Figure 8. Function of the control electronics.

The Amplifier sub-chassis secures the individual amplifiers to the AMP chassis. This is designed to provide a thermal path to the chassis and to provide a favorable orientation with respect to the chassis air-flow pattern. The frame of the Amplifier sub-chassis contains all necessary amplifier interface wiring. This makes the design highly modular to facilitate rapid check out and trouble-shooting.

The safety control electronics consists of the control electronics board and the brake relay board. The purpose of the braking function is to hold the motors in place when they are not under amplifier control. Programmable Logic Devices (PLDs) in the safety control electronics module monitors amplifier power, operator control buttons and the PANIC-HALT button, and a watchdog signal from the high-level software and control processors (indicating that they are healthy). Any anomaly triggers brakes to be set on the slave robot joint and a fault LED to be lighted. The operator must reset the safety control electronics to re-activate the system. A diagram of the safety control electronics functions and PLD state transitions are shown on Figures 8 and 9.

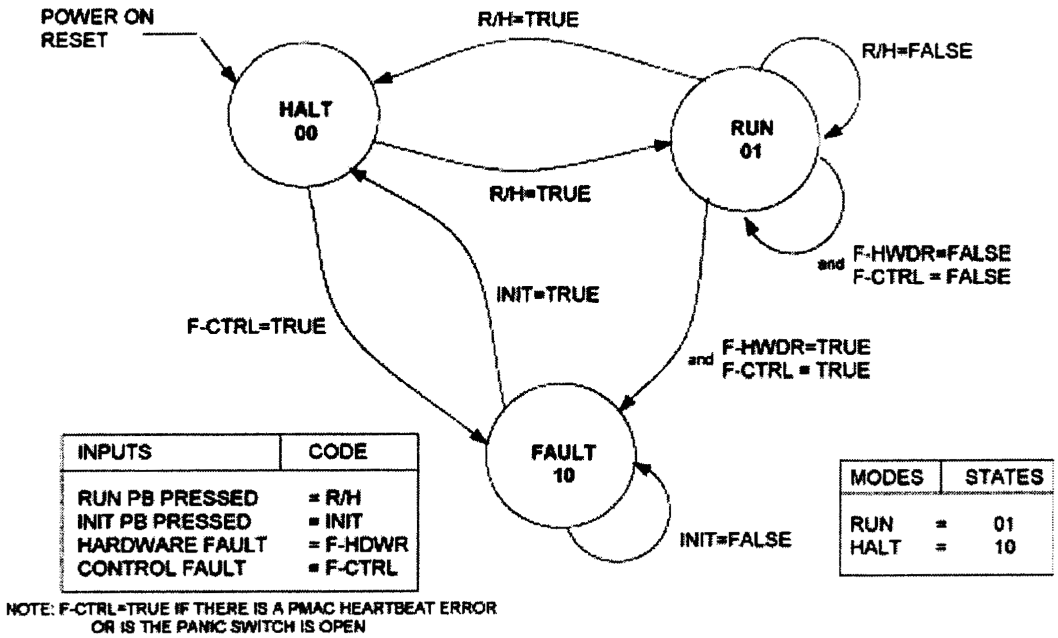

Figure 9. Control electronics state transitions.

Servo-control subsystem

The RAMS servo-control system is implemented on processor boards and servo-control boards installed in a VME chassis. One Motorola MVME-167 and two MVME-177 boards, named Proc0, Proc1 and Proc2, are installed on the VME chassis and run under the VxWorks operating system. Proc0 performs kinematic, communication and high-level control functions for the master robot. Proc1 performs the same functions for the slave robot. These functions are described in the High Level Software Architecture Section. Calls to subroutines that read and set joint angle positions of the robot are made from the high-level real-time software on Proc0 and Proc1. These routines, through shared memory implemented between Proc0 and Proc2, provide set-points and read current joint angles of the robot. Proc2, in turn, passes the set-points for controlling the robot to the servo control board and retrieves the joint angles measured by the servo-control board. The servo level control system uses the PMAC-VME board by Delta Tau. The interface for reading the force sensor is also implemented on Proc2.

Low-level, high-speed communication between Proc0, Proc1, Proc2 and the PMAC-VME boards is through shared memory. The PMAC board has a large variety of features for motor control, with a customer base largely from industrial installations. The key features used for control of the RAMS robot include:

- Digital sine-wave commutation.
- Automatic trajectory generation.
- Shared memory interface.
- Built-in amplifier/encoder interface.
- Robust closed loop control.

High-level software subsystem

There are a number of components to the high-level software for the RAMS slave robot. A drawing of the parts of the software is shown on Figure 10. Embedded in the computational blocks of the real-time control software are the kinematic control algorithms. They are based on algorithms developed at JPL[11,12] for the unique geometry of the robot. Wrist kinematics for the slave robot are based on the work of Williams[16]. The demonstration of different control modes of the robot was implemented using a software development tool for real-time systems called Control Shell[8,9]. Handling of operator commands in the real-time software, transitions between states of control, changes in data flow due to transitions of states in the software and the algorithms executed within computation blocks. The user specifies the control modes of the system through a graphic user interface (GUI) implemented with Tcl/Tk[7]. Commands entered into the GUI are transmitted over an Ethernet connection or by a serial interface and are received on the real-time software side of the system. The message passing between the 2 parts of the software system uses NDDS[10]. A producer part creates the messages and broadcasts them from the GUI part of the system and a consumer part receives the messages and processes them.

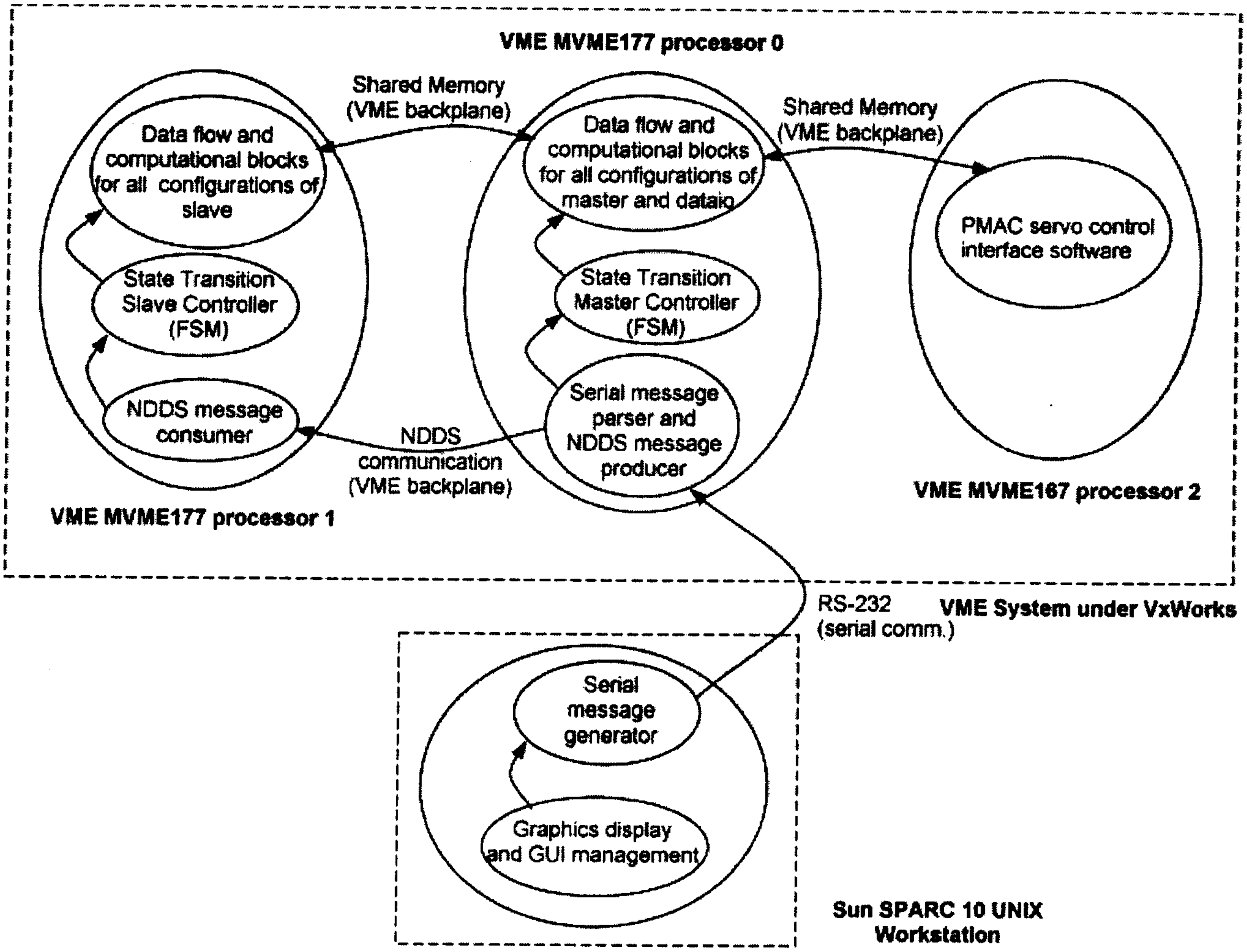

Figure 10. Parts of the high-level software.

Simulated Surgery

In September of 1996, a demonstration of a simulated eye microsurgery procedure was successfully conducted using the RAMS telerobotic system. The procedure demonstrated was the removal of a microscopic 0.015 inch diameter particle from a simulated eyeball.

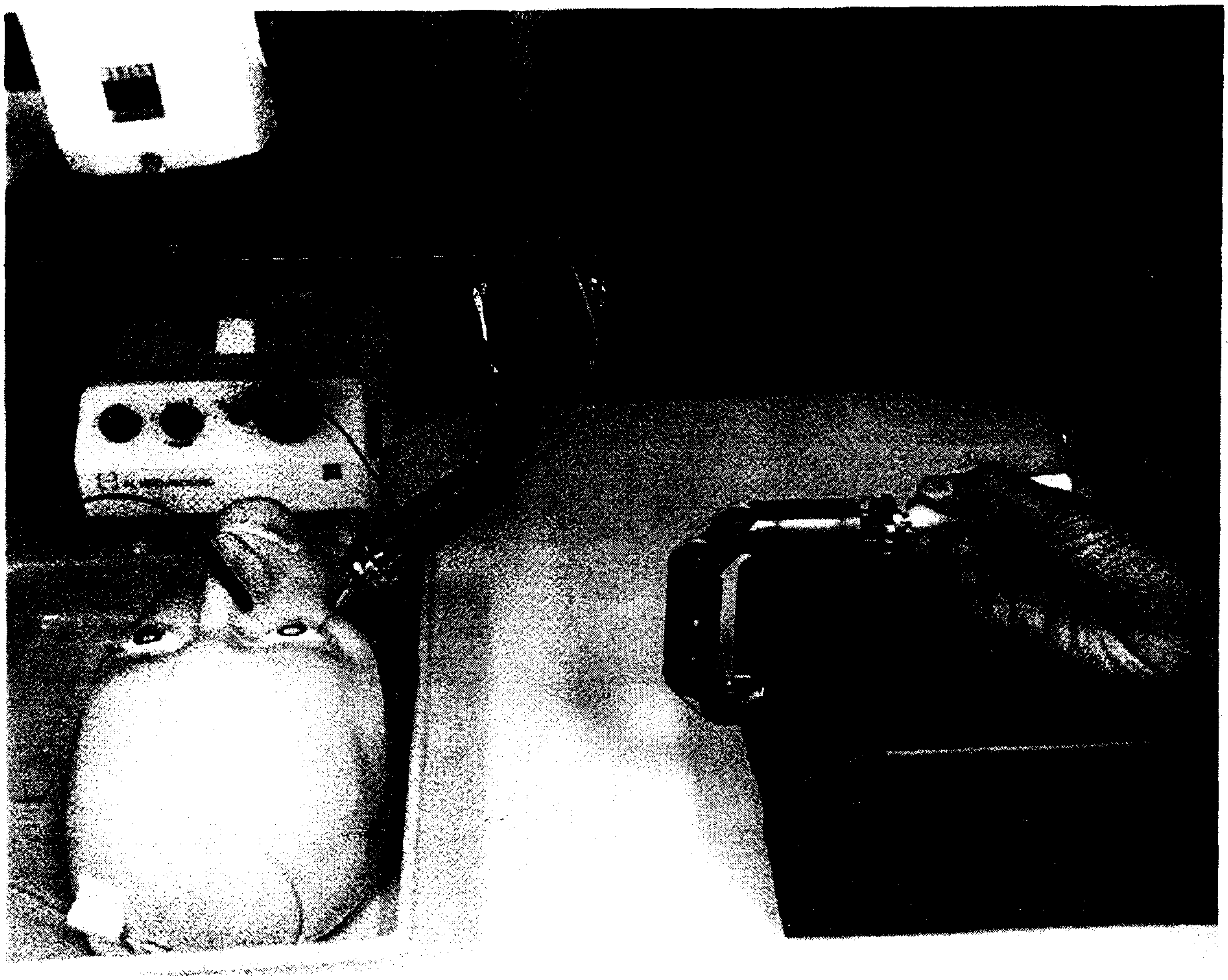

Figure 11. Eye microsurgery demonstration with the RAMS system.

Features added to the RAMS system to enable successful performance of the eye surgery demonstration were switch operated indexed motion, a surgical instrument mounted on the slave robot tip and a pivoting shared control algorithm to automatically compensate for pitch and yaw orientation of the surgical instrument while the operator controls the x-, y-, z- and roll motions of the instrument. Figure 11 shows the RAMS system as seen performing the simulated eye microsurgery procedure.

A dual-arm suturing procedure was also demonstrated. Two prototypes of the RAMS system shown on Figure 12 were configured as left- and right-arms to perform the procedure. Nine-O nylon suture was used to successfully close a 1.5 mm long puncture in a thin sheet of latex rubber.

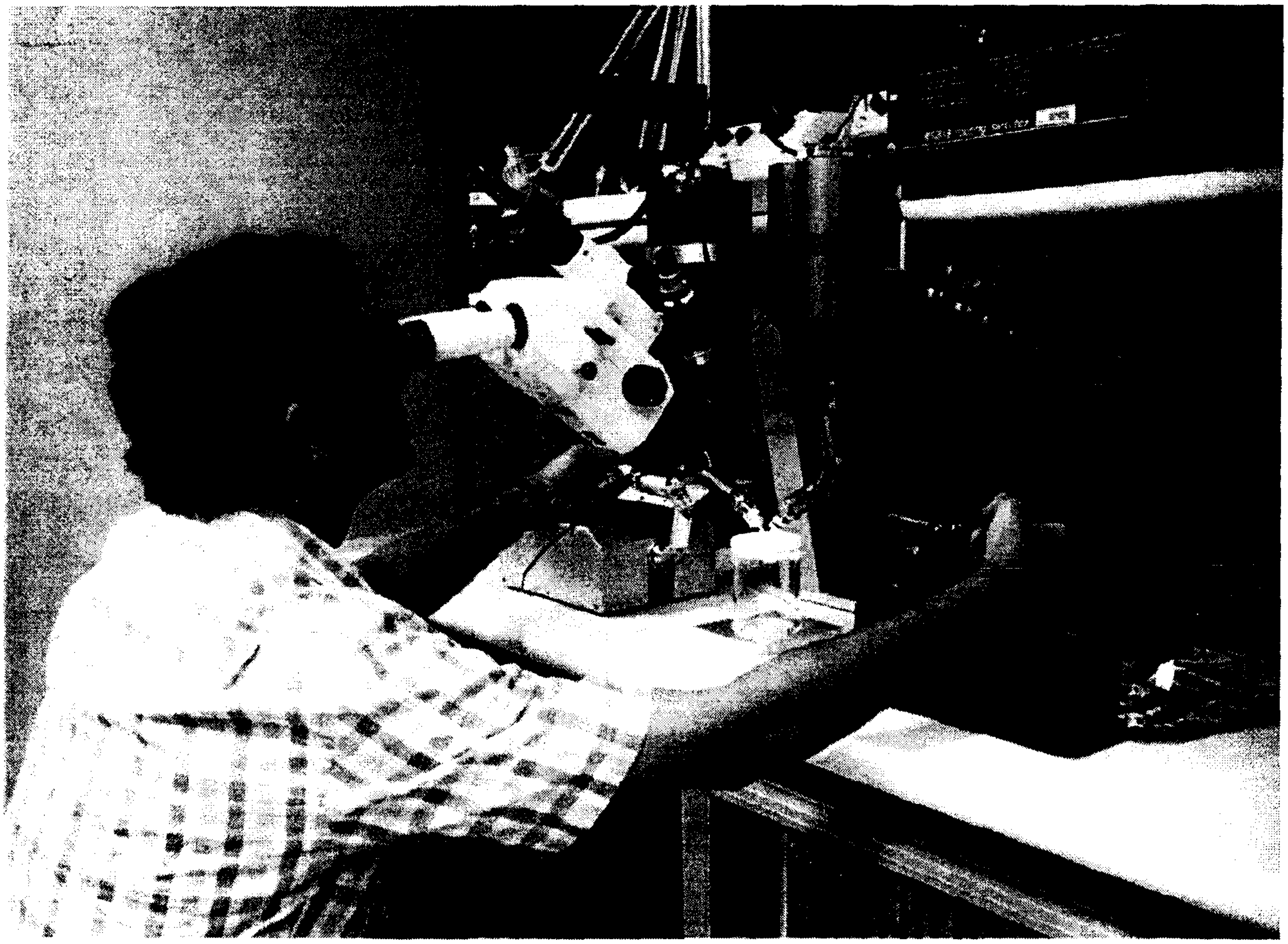

Figure 12. Dual-arm telerobotic suturing demonstration.

Virtual Reality Applications

While the RAMS system was not developed as a Virtual Reality (VR) system, components of it are applicable in VR. The master arm is a unique haptic device that can present virtual or real force interaction to the user. It's ability to measure hand motions to 25 microns in translation and to 0.07 deg. in orientation and its pencil grasp make it ideal as an interface for positioning and *feeling* a probe in a virtual environment. Simulated spring-damper and constrained-motion-within-a-sphere environments have been implemented in tests conducted on the master device.

Synthetic fixtures or virtual augmentation to the real environment was also been implemented on the RAMS system to assist the user in performing complex tasks. In the eye microsurgery simulation procedure, constraints on the motion of the slave robot was implemented to allow the surgical instrument mounted on the slave robot to pivot freely about the entry point in the eyeball. Activation of this mode caused loss of user control in 2 degrees of freedom of the slave robot; the automated control system prevented motion that would move the instrument against the eyeball wall. An alternative to this strategy would be to simulate forces on the master handle that would guide the user into making safe motions.

Although we have not implemented this, the user interface part of the RAMS system can also be used as a simulator to train for microsurgical procedures. Expert guidance to a novice can also be implemented by having the motions made by an expert on a master device be replicated on a similar device held by the novice.

The RAMS system can also serve as a data collection system for measuring the hand motions made by an operator of the system. This data is useful for characterizing the performance of the user. Much may be learned from analysis of this data including characterizing the potential microsurgical abilities of surgical residents, predicting the skill-level of a surgeon at any time or providing some insight into the nature of highly skilled manual dexterity.

Conclusion

The RAMS project at JPL was recently concluded as planned at the end of its 4-year development. A number of accomplishments have resulted from this work. We have demonstrated dramatic improvement over manual surgical instrument positioning. Microsurgeons who have evaluated or seen the prototype built have been very enthusiastic about its potential. There is a growing commercial interest in this technology and its application partly as a result of the success of this development. We have demonstrated practical utility of this technology in microsurgical settings. The products from this work have been transferred to our industry partner, MicroDexterity Systems, Inc. for further development and commercialization. Further augmentation to this system with advanced control and sensors would enable the performance of new procedures not possible with current techniques. The technology developed in this project has the potential to revolutionize the practice of microsurgery by extending the manual dexterity of microsurgeons allowing more surgeons to perform the difficult procedures currently only performed by the most skilled surgeons.

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